Advanced Telescope for High Energy Nuclear Astrophysics (*ATHENA*)

W.N. Johnson, C. Dermer, R.A. Kroeger, J.D. Kurfess,
Naval Research Laboratory, Washington, DC 20375

N. Gehrels, *NASA/GSFC, Greenbelt, MD*

J. Grindlay, *Harvard College Observatory, Cambridge, MA*

M.D. Leising, *Clemson University, Clemson, SC*

T. Prince, *Caltech, Pasadena, CA*

W. Purcell, *Northwestern University, Evanston, IL*

J. Ryan, *University of New Hampshire, Durham, NH*

T. Tumer, *University of California, Riverside, CA*

ABSTRACT

We present a space mission concept for a low energy gamma-ray telescope, *ATHENA*, which is under investigation as the next major advance in gamma-ray spectroscopy following the current *COMPTON Gamma Ray Observatory* and the planned *INTEGRAL* missions. The instrument covers the nuclear line emission energy domain with dramatically improved sensitivity and spectral resolution. The baseline configuration combines a high resolution Compton telescope constructed from Ge planar strip detectors for the 0.3 – 10 MeV energy region with a coded-aperture system for the 10 – 200 keV domain. The Ge Compton telescope provides a broad field of view with exceptional spectral and imaging resolution. The requirements, capabilities and simulations of *ATHENA* are discussed.

Keywords: Gamma Ray Astronomy, Germanium Detectors, Imaging

1 INTRODUCTION

Improved space missions in gamma ray spectroscopy are essential for the understanding of many of the fundamental problems in astrophysics. We have been investigating the characteristics of such a mission, the Advanced Telescope for High Energy Nuclear Astrophysics (*ATHENA*), which would be required to achieve significant improvements in sensitivity compared to those achieved by the *COMPTON Observatory (GRO)* and planned for *INTEGRAL*. This will also be accomplished with excellent energy and angular resolution. Specifically, we envision improvements in line gamma ray sensitivities of a factor of 20 – 50 for narrow lines to a few $\times 10^{-7} \gamma$ cm^{-2}s^{-1}, with simultaneous high resolution spectroscopy and imaging over the entire gamma ray spectroscopy band. These capabilities will provide important new information on a broad range of scientific objectives. For example, *ATHENA* will: 1) Map the Galaxy, for the first time and with good angular resolution, in line emissions from ^{26}Al, positron

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1995**	2. REPORT TYPE	3. DATES COVERED **00-00-1995 to 00-00-1995**
4. TITLE AND SUBTITLE **Advanced Telescope for High Energy Nuclear Astrophysics (ATHENA)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7213,4555 Overlook Avenue, SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

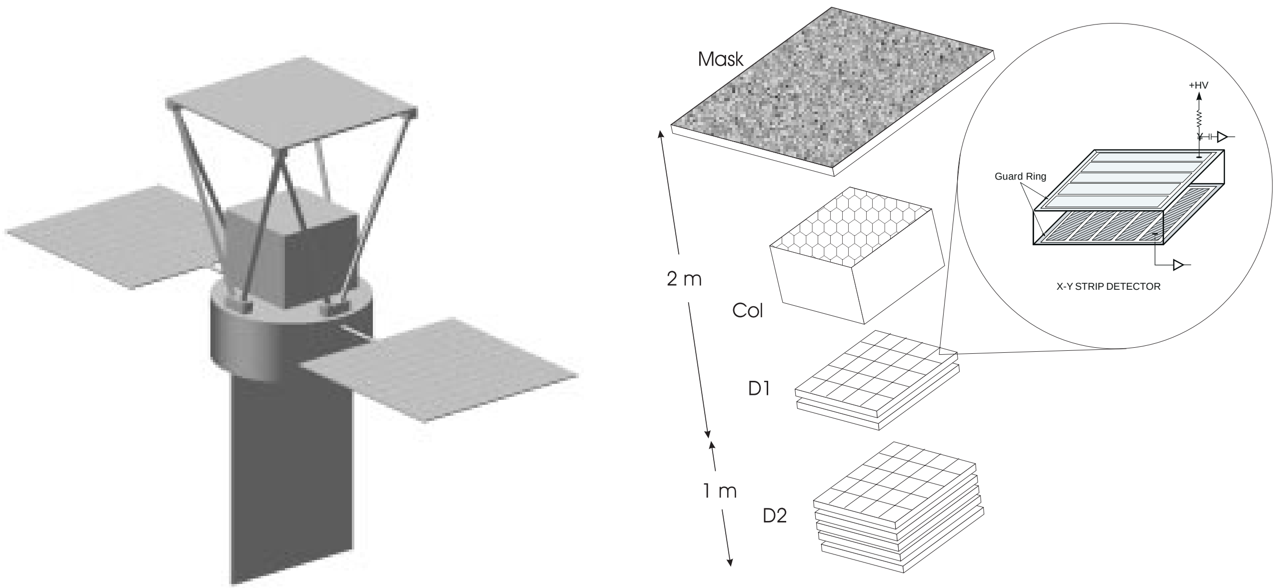

Figure 1: *ATHENA* spacecraft concept (left panel) displays the coded-aperture mask above the detectors and includes articulated solar panels and a large passive radiator below. The right panel displays a conceptual diagram of the combined coded-aperture imager and the Compton telescope. The Compton telescope consists of two detector planes (D1 and D2). A coded mask is mounted $\sim$ 2 m above the top detector plane, which forms the coded-aperture imager using the top layer of D1. A coarse collimator just above the D1 layer restricts the field of view for the imager.

annihilation, ^{60}Fe, ^{44}Ti, ^{12}C, ^{16}O, ^{56}Fe, and the positronium continuum. These maps will reflect the nucleosynthetic contributions of supernovae, novae, and massive stars, discover many sites of galactic supernovae in ^{44}Ti (last 1000 yrs) and ^{26}Al (last 10^6 yrs) and map interactions of low energy cosmic rays in the interstellar medium and molecular clouds. 2) Detect fresh radioactivity from several extragalactic Type Ia supernovae per year, determine the nature of Type Ia events, and evaluate their use as a cosmic distance indicator. 3) Test the explosive nucleosynthesis models for galactic novae though observations of prompt and long-lived radioactivities. 4) Provide high resolution spectra for several thousand AGN in the low-energy gamma ray region, study evolution of AGN in this energy band where they exhibit peak luminosity, and support multi-wavelength campaigns of AGN. 5) Elucidate the nature of gamma ray bursts with less than arc-minute position determinations, high resolution spectroscopy of several hundred events, and sensitive searches for post-burst emission. 6) Determine the surface gravitational fields of neutron stars by redshift measurements of nuclear line emission and thereby constrain the equation of state of neutron star material. 7) Determine the character and origin of the cosmic gamma ray background.

The instrument concept, shown in Figure 1 combines a high spectral resolution Compton telescope with a coded-aperture hard X-ray imager. The Compton telescope covers the energy range from $\sim$ 300 keV to above 10 MeV, while the coded aperture covers the energy range from about 10 keV to 200 keV. There are clear advantages for selecting this configuration. In the energy region above several hundred keV, the Compton telescope combines outstanding performance for both discrete and diffuse sources. This is of utmost importance, for there are many key spectroscopy objectives for both discrete and diffuse emission. For example, many narrow lines are expected from galactic diffuse emission and

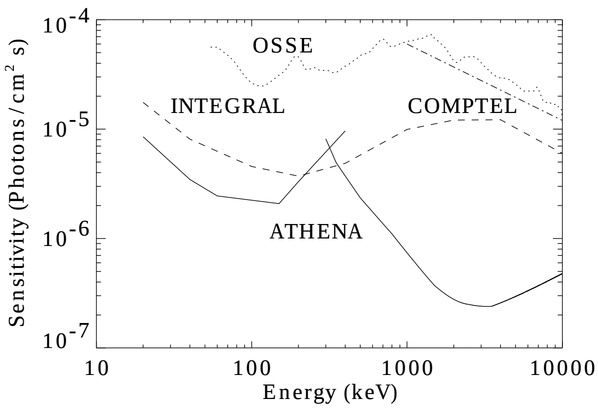

Figure 2: Sensitivity comparison for narrow lines (left panel) for *ATHENA*, *INTEGRAL* and the OSSE and COMPTEL instruments on *GRO*. The right panel compares sensitivities for broad lines typical of Type Ia supernovae (5000 km/s expansion). *ATHENA* sensitiivites for the coded-aperture (lower energy) and Compton telescope components are shown separately.

cannot be observed with high sensitivity using coded-aperture techniques. A high-spectral resolution spectrometer, e.g. using position-sensitive germanium detectors, achieves outstanding sensitivity while also providing excellent imaging capabilities, with angular resolutions approaching $0.2 - 0.3$ degrees. This is more than a factor of ten better than previously achieved for low-energy γ-rays. The excellent spatial and energy resolutions of the upper detector of the Compton telescope are also very well suited to its use in a coded aperture hard X-ray imager which can provide outstanding angular and spectral resolution.

Figure 2 shows the estimated sensitivities for *ATHENA* for both narrow and doppler broadened lines. The latter are characteristic of Type Ia supernovae. The sensitivities for the *GRO* instruments and for the planned *INTEGRAL* mission are shown for comparison. All sensitivities shown are 3 σ detection sensitivities for an observation time of 10^6 s.

Note that *ATHENA* has excellent sensitivities in the energy range from about 0.5 – several MeV. This region covers most of the astrophysically interesting narrow line features, including the 511 keV positron annihilation line, ^{56}Co lines from 847 keV to 3260 keV, ^{44}Ti at 1156 keV, ^{22}Na at 1275 keV, ^{26}Al at 1809 keV and the n-p capture line at 2.223 MeV. The sensitive improvement for *ATHENA* in the region for nuclear lines is clear. It should also be noted that the sensitivity of *INTEGRAL* for narrow lines from diffuse sources (comparable to and larger than the few degree angular resolution of the *INTEGRAL* spectrometer coded aperture) will be similar to its broad line sensitivity.

As an example of the capabilities of *ATHENA*, we have undertaken a simulation of an *ATHENA* observation of the Vela supernova remnant. This remnant is the result of a supernovae which occurred about 11,000 years ago at a distance of about 500 pc. The remnant covers a region about 8 degrees in diameter. The COMPTEL instrument on the COMPTON Observatory has recently reported[3] the weak detection of ^{26}Al emission at 1809 keV with a flux of 3.6×10^{-5} γ cm^{-2} s^{-1}.

Recent ROSAT results[1] have provided an X-ray map of the remnant and reported the discovery of

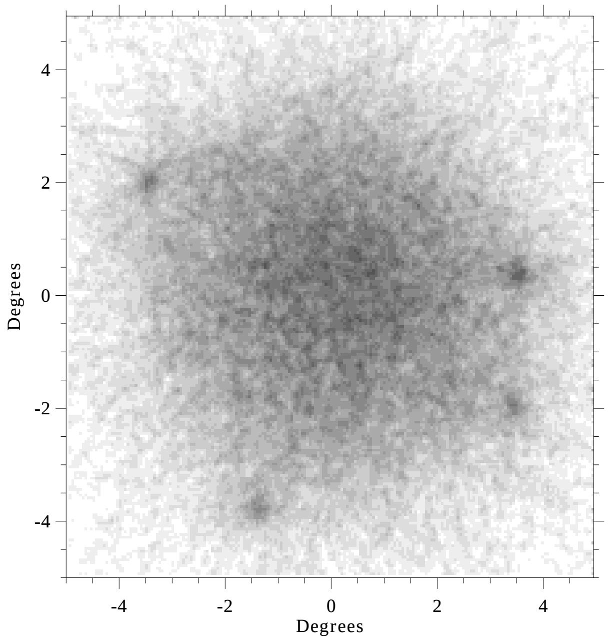

Figure 3: Simulation of a 10^6 sec *ATHENA* observation of the Vela supernova remnant in the 1809 keV line of ^{26}Al. The combination of excellent spatial resolution and sensitivity enable several components of the remnant to be seen, including hypothetical radioactivity in the explosion fragments detected by ROSAT.

explosion fragments which are presumed to be blobs of material from the inner part of the pre-supernova star which are now penetrating the supernova remnant shock wave boundary. For the *ATHENA* simulation we have assumed that the bulk of the aluminum radioactivity ($\tau = 10^6$ yrs) is distributed within a region bounded by the inner 2–3 degree radii, but that a few percent of the ^{26}Al is contained in each of four explosion fragments. The simulation, Figure 3, shows that *ATHENA* could resolve the ^{26}Al in the fragments and map the distribution of ^{26}Al in the central regions of the remnant. These data would provide important new information on both the nucleosynthetic yields of supernovae as well as the dynamical effects on material near the core of the explosion.

2 INSTRUMENT CONCEPT

Significant improvement over current gamma-ray instrumentation requires both high resolution spectroscopy and good angular resolution imaging in the hard X-ray and low-energy gamma-ray energy band. A large field of view and good sensitivity to diffuse emissions are critical to meet the scientific objectives in nuclear line astrophysics. The Compton scatter telescope is unique in its ability to meet these diverse requirements. We have investigated one such system created from germanium planar strip detectors which can provide $2-3$ keV spectral resolution and spatial resolution of ~ 2 mm. These detectors, which are ~ 5 cm $\times$ 5 cm $\times$ 1 cm, are excellent hard X-ray detectors and can be layered to provide good efficiency to 10 MeV. Compton scatter telescopes using multiple layers of these detector arrays could achieve imaging resolution of a few tenths of a degree in the soft gamma ray range above ~ 300 keV. A hard X-ray capability is provided by adding a coded aperture mask above the Compton telescope which provides a modulated hard X-ray field-of-view for the top array of Ge strip detectors. The coded-aperture hard X-ray mode provides few arc-minute images in a $10-15$ degree field-of-view. This configuration, shown conceptually in Figure 1, can be scaled to sizes with impressive sensitivities

and optimized to provide a system with good spectral and imaging resolution from ~ 10 keV to 10 MeV.

Compton scatter telescopes use two detector planes designed to scatter the incident radiation in the top plane (D1) and capture the scattered photon in the lower plane (D2). Measurements of the energy losses and positions of the interactions in the two detector planes permit the reconstruction of the incident photon direction. In telescopes such as the one considered here, and COMPTEL on COMPTON,[11] it is not possible to measure the direction of the Compton electron in the top detector. Consequently the possible directions, when projected onto the sky, produce a circle of the half-angle specified by the scatter angle and centered on the direction of the scattered photon. A point source of gamma rays is detected at the intersection of many such circles. Uncertainties in the energy loss measurements and in the interaction positions change the circle to an annulus and ultimately determine the angular resolution of Compton telescopes. Simultaneous improvements in spectral resolution and detector spatial resolution, as available in Ge planar strip detectors, are required to achieve good angular resolution in these systems. We have modeled a Compton telescope system constructed from Ge planar strip detectors with 2-mm pitch strips and 2 keV energy resolution. As discussed below, orthogonal strips on the two surfaces of the detector provide 2-dimensional spatial information with 2 mm resolution.

The Compton telescope is summarized in Table 1 (see also Figure 1). The top detector plane (D1) is formed from an array of strip detectors in two layers to provide ~ 1 m^2 active area. The bottom plane (D2) is ~ 1 m below D1 and comprised of five layers of strip detectors. Each layer is ~ 1.4 m square and constructed from ~ 400 detector elements similar to the type shown in the figure inset. The coincidence requirement for energy losses in the D1 and D2 planes produces systems with relatively low efficiency, generally $1-3\%$, but also greatly reduces the detector background, more than compensating for the low efficiency. Monte Carlo simulation of the on-axis efficiency for this configuration as a function of incident photon energy indicates $\sim 2\%$ efficiency at 250 keV peaking at $\sim 3\%$ in the 400 keV to 1 MeV range, and down to $\sim 1\%$ by 10 MeV. For incident angles of 30° off-axis, the response is $\sim 80\%$ of the on-axis response. Below 200 keV, the coded aperture telescope using the D1 plane of detectors provides good response down to ~ 20 keV. As displayed in Figure 1, a coded mask formed from ~ 1 mm-thick tungsten or tantalum is placed 2 m above the D1 layer. The thickness is selected to provide good modulation of hard X-rays but thin enough to be reasonably transparent to higher energy photons. The figure also shows a coarse collimator which is required in restricting the hard X-ray field of view.

The Ge-Ge Compton telescope offers significant capabilities compared to the instruments on *COMPTON* and the *INTEGRAL* study instruments.[6,2] As with COMPTEL on *GRO*, it has a large field of view ($\sim 60^\circ$) and has the ability to image diffuse emission such as the ^{26}Al emission from the Galaxy. Its excellent spectral resolution and 2 mm spatial resolution provide significant improvements over COMPTEL in spectroscopy, point source imaging and sensitivity. Improvements in sensitivity to continuum emissions by $\times 10$ appear to be achievable. The Ge spectroscopy and low background of the Compton configuration will provide significant sensitivity to narrow line emissions. Figure 2 shows the narrow line sensitivity of the Ge Compton telescope relative to current capabilities (OSSE,[5] COMPTEL[11]). The limiting sensitivity for point sources is determined by Monte Carlo response to the cosmic diffuse background. Other sources of background, such as local gamma ray production, spallation products and neutron interactions, have been estimated to be $\sim 3\times$ the contribution of the diffuse cosmic background. The figure also shows the low energy response of the coded-aperture telescope where we have assumed a 10° field of view.

Compton telescopes as employed in space and on balloon platforms are instruments designed to

Table 1: *ATHENA* Instrument Characteristics

Upper Detector Assembly (D1)	
Detectors:	5 cm $\times$ 5 cm $\times$ 1 cm planar Ge
Detectors/Layer	400 (10,000 cm^2 total area)
Layers	2
Total Strips	40,000
Position Resolution	2 mm
Energy Resolution	2.5 keV (at 1 MeV)
Energy Range	10 keV – 2 MeV
Lower Detector Assembly (D2)	
Detectors:	5 cm $\times$ 5 cm $\times$ 1.5 cm planar Ge
Detectors/Layer	400 (10,000 cm^2 total area)
Layers	5
Total Strips	100,000
Position Resolution	2 mm
Energy Resolution	2.5 keV (at 1 MeV)
Energy Range	25 keV – 5 MeV

measure generally weak cosmic gamma ray sources in a high background environment. Much of the "gamma ray" background in monolithic spectrometers in space is, in fact, a result of radioactive decays in high Z inorganic detecting material or the result of neutron interactions in the same material. Either type of reaction produces an ionizing particle that is measured by the detector, whether it be a scintillator or a solid state detector. A Compton telescope requires a coincidence detection in two independent detectors. Fast timing to establish the event sequence in the two detectors is a powerful technique for background reduction. Alternatively, event reconstruction of the energy loss patterns in the two detectors can also be effective in discriminating the direction of the incident γ-ray. The ideal instrument would combine both the timing and spatial resolution techniques.

The Compton scattering formula gives the relation between the incident and scattered gamma rays and the angle of scattering as:

$$\cos\phi = 1 - \mathrm{mc}^2\left(\frac{1}{\mathrm{E}'} - \frac{1}{\mathrm{E}}\right)$$

where ϕ is the scattering angle and E and E' are the energies of the incident and scattered gamma ray. Knowing the locations of the interactions of E and E' in the upper and lower detectors and the corresponding energy losses, the incident gamma ray must lie on a cone of half width ϕ and whose axis is the line joining the location of interactions in the two detectors. The uncertainty in the scatter angle is given by:

$$\Delta\phi = \frac{\mathrm{mc}^2}{\sin\phi}\left\{\frac{\Delta\mathrm{E}_u^2}{\mathrm{E}^4} + \Delta\mathrm{E}_l^2\left(\frac{1}{\mathrm{E}_l^2} - \frac{1}{\mathrm{E}^2}\right)^2\right\}^{1/2}$$

where $\Delta\mathrm{E}_u$ and $\Delta\mathrm{E}_l$ are the uncertainties in the energy deposited in the upper and lower detectors, ϕ is the scattering angle, and mc^2 is the rest mass of the electron. The much smaller uncertainty in the

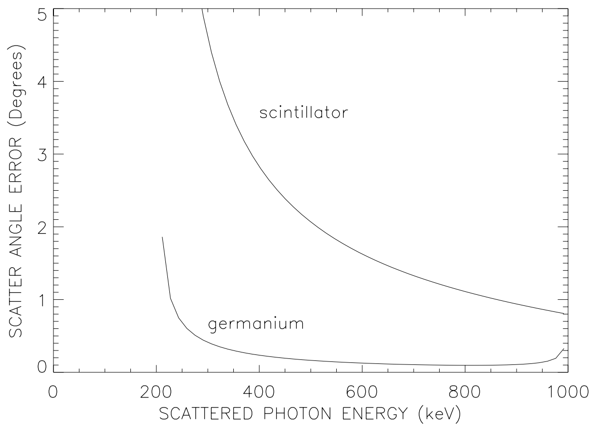

Figure 4: Comparison of scatter angle error, $\Delta\phi$, for Ge and scintillation detectors for an incident 1 MeV photon.

scattering angle when using high spectral resolution detectors results in a much improved location on the sky for point sources from which the gamma rays originate, and the improved location results in improved sensitivity due to the lower background associated with the point source search. Figure 4 shows a comparison of the error in the scattering angle for Compton telescopes using scintillation detectors (such as COMPTEL on *GRO*) and germanium detectors for 1 MeV incident gamma rays. The factor of $\sim$ 10 reduction over the 600–950 keV effective energy range for the scattered γ–ray is obvious.

The useful energy range of a Compton telescope extends from the energy where the photoelectric cross section falls below the Compton scattering cross section (100–200 keV for the materials considered here) to above 10 MeV where the pair production cross section can start to dominate. Dual-scintillator Compton telescopes are limited to operate in the range from $\sim$ 700 keV to $\sim$ 20 MeV. (Small Compton scatters, necessary for good imaging properties, require D1-detector thresholds below 30 keV.) By employing high resolution solid state detection techniques in D1, this lower energy limit falls well below 511 keV, an energy of astrophysical importance. The sensitivity of Compton telescopes can be significantly improved if the direction of the recoil electron can be measured in D1. This may be possible above 1–2 MeV in silicon strip detectors, a technique that is currently under development.[12] Imaging and sensitivity can also be improved by increasing the fraction of fully absorbed events in the D2 detector.

A significant advantage in spectroscopy follows from the equivalence of the scattering geometry and the measured energies through the Compton kinematic formula. That is, a photon from a point source that is registered in the instrument whose annulus passes through the position of the source has had its entire energy collected and measured. This increases the resolving power of the instrument by systematically excluding partially measured events.

Germanium detectors have unquestionably the best energy resolution of any practical gamma-ray detector. New technologies in germanium detectors are now permitting a combination of position resolution along with excellent spectroscopy which is generally expected from germanium. Recent developments in this field include germanium strip detectors.[4,10] Spatial and energy resolution of a Ge strip detector with 2 mm pitch is demonstrated.[8,9]

The diagram of a germanium strip detector now in our laboratory is shown in Figure 5. This

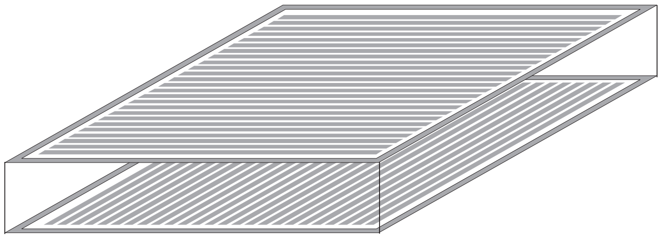

Figure 5: Schematic of the 2 mm pitch germanium strip detector. Crossed electrodes provide two-dimensional position localization of interactions. The electrodes are read out individually. There are 25 strips on each face of the detector.

detector provides 2 mm position readout by identifying the strips where an interaction occurs.[9] Our measurements indicate that the sharpness of the strip edge is less than 1 mm, indicating the potential for sub-mm position resolution is likely. CMOS electronics are being developed for germanium detectors.[7] Alternative detector contact technologies are being explored to replace the lithium contacts that are now in use. These alternatives could provide finer spatial resolution and longer detector shelf life. Germanium pad detectors are also possible, where position is determined on one face of the detector using a large number of cathode pads, and energy for the entire detector volume is measured using a single contact on the anode face. The pad detector concept uses fewer channels of spectroscopy electronics and may improve overall spectroscopy and timing performance. CdZnTe detectors are room temperature semiconductors with the promise of fairly good energy resolution over modest active volumes. Problems with hole trapping have limited the useful energy range to below $\sim$ 100 keV for this application. However, new techniques to compensate or eliminate the signal contribution from the holes are encouraging,[10] and may lead to large volume, higher energy detectors. Strip contacts and pixelated contacts are currently under development. Difficulties in making reliable electrical contacts to the detector must be overcome. There are good prospects for detectors with sub-mm strips becoming available within the next one to two years.

As summarized in Table 1, the baseline *ATHENA* has 140,000 Ge strips, each with its own preamp and analog signal processing. This number of electrical connections presents not only a complication for the instrument electronics but also a significant heat load which must be handled to maintain the Ge detectors at 80°K. The estimated power and complexity of this configuration is based on this number of signal chains, but multiplexing concepts could dramatically reduce the number of signal chains and thus the heat load. Power estimates for the signal chain are based on CMOS application specific integrated circuits (ASICs) currently under test at the Naval Research Laboratory and Oak Ridge National Laboratory.[7] These circuits provide preamp, shaping amp and analog to digital conversion. Continued development of such circuits could improve the power/performance of the system.

3 MISSION REQUIREMENTS

The requirement for cryogenic temperatures for the Ge detectors plays a large role in the consideration of mission profiles for this instrument. One of the optimum missions observes from geosynchronous or higher orbit. The geosynchronous orbit is advantageous because 1) the heat load from the earth is small enough to permit efficient cooling with passive radiators with little restriction on viewing direction, 2) mission operations can be performed from a single ground station, and 3) the orbit is above most trapped radiation belts, consequently reducing activation background. The concern with regard to high earth orbits such as geosynchronous is the cost of the launch vehicle necessary to achieve such

Table 2: *ATHENA* Mass Estimates (kg)

Instrument		1976 kg
Detector	1000	
Collimator	96	
Coded Aperture	71	
150K Shield	30	
Baseplate	200	
Mech. Coolers	100	
Strut/mech. support	50	
Cabling	73	
Electronics	356	
Spacecraft		1430 kg
Primary structure	440	
ACS/Propellant	170	
C&DH	60	
Power/Solar Arrays	280	
Thermal/Radiator	430	
Misc.	50	
Margin		340 kg
TOTAL		3746 kg

an orbit.

An optimum instrument configuration consists of two temperature stages, the Ge detectors cooled to 80°K by mechanical cryocoolers and an intermediate temperature stage which is passively cooled by a radiator to $\sim$ 150°K to reject detector parasitic and preamp heat loads. The instrument interfaces to the spacecraft via an aluminum baseplate (Figure 1). The detector assembly, collimator and 150°K shield assemblies are mounted to the baseplate by a set of thermally isolating alumina/epoxy struts. The coded mask is mounted to the baseplate by a set of graphite/epoxy struts. The detectors are hermetically sealed units but are not placed in a vacuum cryostat; the system would be launched warm and cooled down once in orbit. The spacecraft interface plate provides an o-ring interface for a vacuum shell that can be used for ground testing of the instrument (without coded mask). This alleviates the need for a large vacuum chamber and allows instrument testing in almost any laboratory. Spacecraft system-level testing would require a large vacuum chamber.

The detector assembly is cooled by split, linear, Stirling-cycle coolers; other viable mechanical cooler options may exist for consideration in the future. Cryocoolers are mounted to and reject their heat to the baseplate. The conceptual instrument design has a complement of coolers consisting of four primary units plus two backup. The cooler cold tips are connected to the detector assembly by capillary pump loops, which are currently in development. These provide an efficient thermal connection between the cooler and heat load during operation and an effective thermal disconnect when the cooler is shut off (thus minimizing the parasitic heat load from the non-operating cooler). The detector assembly

Table 3: *ATHENA* Mission Summary

Mass	3800 kg
Orbit	Geosynchronous (40,000 km)
Mission Life	5 years
Pointing	Any direction, any time
Attitude Stability/Knowledge	30 arc sec/ 10 arc sec
Telemetry	3 Mbps
Power	2500 W

is surrounded on the sides and bottom by a radiation guard shield cooled by a passive radiator at a temperature of 150°K. Heat is moved from the shield and preamps to the radiator by a capillary pump loop. The 150°K radiator is a folding flat panel design much like for the space station and is stowed for launch and deployed once the instrument is on station. The collimator is positioned above D1. Multilayer thermal insulation blankets inside and outside the shield and collimator control the parasitic radiation. The cooling requirements are estimated to be a 12 W load on the 80°K stage and 310 W on the 150°K stage. For mission resource estimates we have used a cooler efficiency of 35 W/W typical of current coolers and a passive radiator based on a radiating power of 15 W/m^2 .

Figure 1 shows the baseline concept of the *ATHENA* spacecraft. The deployed configuration is 2.8 m in diameter and 4.6 m long (exclusive of the 150°K radiator). The design incorporates articulated solar panels to permit instrument viewing in any direction at any time. A large passive radiator extends below the spacecraft and is aligned and shielded to avoid direct illumination by the sun. In geosynchronous orbit, the passive radiator does not need to be articulated since the radiator plane is aligned with the solar flux vector and radiation from earth is minimal at that distance. Articulated RF antennas (not shown in the figure) are used for RF communications.

Table 2 summarizes the weight estimates for *ATHENA*. These estimates are based on existing technologies and previous S/C designs. The power system includes 200 amp-hr batteries which provide approximately 2 hours backup; the eclipse of the sun from geosynchronous orbit does not exceed 70 minutes. The command and data handling (C&DH) system assumes 3 Mbps continuous data stream. The telemetry rate was sized to provided event-by-event transmission of data for both the Compton telescope and coded-aperture modes, thereby preserving optimum imaging and spectroscopy throughout the entire energy range. A 3-hour solid state data buffer has been included to stage data during RF communications outages. Table 3 provides a summary of the *ATHENA* mission.

4 CONCLUSIONS

The studies to date indicate that imaging systems utilizing planar germanium strip detectors can provide significant improvements in gamma ray spectroscopy and imaging over the current *COMPTON GRO* and the planned capabilities of the *INTEGRAL* mission. The Compton telescope using these

detectors appears to be the best approach for simultaneously achieving good sensitivity to point and diffuse emissions. There are, however, many technical challenges and investigations which remain to be addressed. Some of these challenges are cryogenic support for the array of planar detectors and low-power and high-density electronics for the strip detectors. Investigations are continuing into the background components, the ability to perform time-of-flight background rejection between the two detector planes and background rejection using parent reconstruction. We will continue to investigate these issues in preparation for the next major gamma ray astronomy mission opportunity.

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